Wide Area Measurement and Protection System for Emergency Voltage Stability Control

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***Abstract* -- When a major power system disturbance occurs, protection and control systems have to limit the impact, stop the degradation and restore the system to a normal state by appropriate remedial actions. Wide area measurement and protection systems limit the severity of disturbances by early recognition as well as proposition and execution of coordinated stabilizing actions. These systems complement classical protection and SCADA/EMS applications. This paper proposes a system design based on Phasor Measurement Units, encouraging system protection schemes for frequency, small signal angle and voltage instability. The system is compared to classical protection and SCADA/EMS systems showing its benefits. A new algorithm for long-term voltage stability prediction is introduced using the proposed system setup.**

***Index Terms* -- Wide Area Protection, Voltage Stability, Voltage Control, System Protection Schemes, Wide Area Measurement, Phasor Measurement Units**

I. Introduction

System wide instabilities or collapses occur frequently in many power systems [1]. Due to the pressure of the market liberalization this tendency will increase. The investment into new lines is limited due to economic and also environmental reasons. Increasing transmission demands caused by the market activities are also stressing systems more and more. This leads to a lack of transmission capacity resp. bottlenecks together with a reduced reliability. The same effect can be seen in non-liberalized power systems of developing countries where the developments of the grid are behind the actual requirements. In both cases alternative solutions are desired which can be integrated easily and cost effectively. Wide area measurement and protection systems [2] provide the opportunity to either

- increase the power transmission capability,
- increase the system reliability, or
- increase both in combination.

Exemplary applications are transmission corridors, which exist in many systems to connect cheap generation areas, e.g. with hydropower, with huge load centers. The strengthening of these corridors with new transmission lines is very expensive. Alternatives with lower investments are therefore desired.

A wide area protection system does for sure not increase the physical transmission capacity but is able to increase the useable capacity. The operation strategy can be modified in the direction of higher used capacity with simultaneously reducing the risk of evolving collapses using a wide are protection system. The value of the transmission capacity must be compared to the costs of probably taken remedial actions. This example shows that wide area protection has a broad field of application against the background of limited transmission capacity due to market pressure or load increase in developing systems.

This paper derives the requirements for wide area protection out of its possible tasks in section II. In section III a general design of a wide area measurement and protection system is proposed. The setup and applications of the proposed system are discussed. Section IV presents details about emergency voltage stability control based on the wide area protection system.

The setup, basic concept and algorithm for this application are introduced. The concept is based on a dynamic voltage instability prediction, which is aimed to counteract evolving cascading contingencies. The advantage of this approach is discussed in comparison to SCADA/EMS-solutions. The applicability of the proposed approach is shown with the example of a real power system.

II. Requirements for a Wide Area Protection System

In the following the requirements for a wide area protection system are derived to fulfil the two tasks of increasing transmission capability as well as system reliability.

Increasing the system reliability means that contingencies or critical events may not lead to a system wide critical situation or even to a system collapse. Therefore a wide area protection system must identify critical situations and determine appropriate remedial actions. The identification together with the actions shall be monitored to the operator and the actions shall be taken, dependent on the time frame of the event, automatically.

Wide area protection applications must distinguish between the following physical phenomena:

- Transient angle instability (first swing)
- Small signal angle instability (damping)
- Frequency instability
- Short-term voltage instability

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- Long-term voltage instability

These phenomena are nowadays partly covered by pure local actions as part of the classical protection schemes or manually on the base of the SCADA/EMS view.

The major drawbacks of these conventional solutions are that local protection devices are not considering a system view and are therefore not able to take optimized and coordinated actions. Even in the case of under-frequency controlled load or generation shedding, the frequency itself is a system information, but the actions are locally taken on predefined design rules. A system view would come into account for example if the set values for the shedding devices are updated according to the actual system status.

The SCADA/EMS system instead is not able to catch the dynamics of the system and is therefore focussed on the steady state operational requirements. Evolving cascaded outages, which might lead to the above instabilities and are going along with a dynamic unfolding system status, are not satisfactorily covered by the conventional solutions. The proposed techniques in [3] are only basing on the steady state SCADA view and therefore missing the under-laying dynamics as part of the evolving problems.

These drawbacks define the major requirements for wide area protection systems:

- Dynamic measurement and representation of events
- Wide area system view
- Coordinated and optimized stabilizing actions
- Handling of cascaded outages

Seen from the time frames where the different systems act, the classical protections are the fastest ones, followed by the wide area protection for fast and system wide operation and the SCADA/EMS system as the slowest view for partly automated and manual operation. Fig. 1 concludes the major requirements in comparison to classical protection and SCADA/EMS-systems.

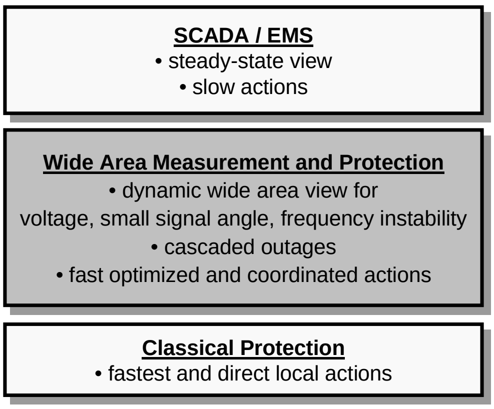

Fig. 1. Categorization and requirements for wide area measurement and protection systems

III. Design of a Wide Area Protection System

A. General System Setup

The following section deals with the design of a wide area protection system, whereas the previous section was focused on the logical and functional definition. The design follows the requirements worked out above.

The basis for a wide area protection system are Phasor Measurement Units (PMU) which fulfill the requirement of a dynamic system view [4]. The PMUs measure time-synchronized voltage and current phasors. Therefore directly comparable measurements are taken as snapshots [5]. The PMU functionality is embedded in local devices, called system protection terminals (SPT), which are able to run certain local algorithms and communicate directly with remote devices and systems like other SPT, substation automation and control or protection centers.

The design of a wide area protection system is determined both by a wide area view and the wish for decentralization due to robustness and speed requirements. A general system setup is shown in Fig. 2.

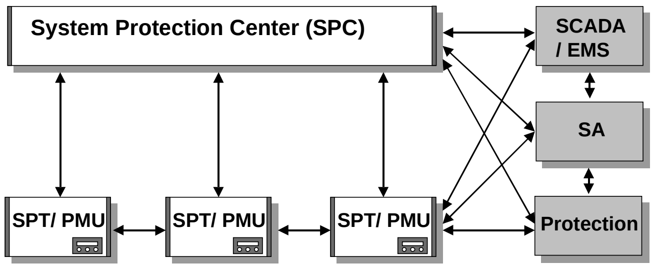

Fig. 2. General system setup of a wide area protection system (SA = Substation Automation, SPT = System Protection Terminal, PMU = Phasor Measurement Unit)

Dependent on the algorithms to be implemented not all communication channels and connections are necessary. The principle difference between the SPC and the SCADA/EMS-system is the complete dynamic view resp. synchronized snapshot of the system state in the SPC. PMUs can also be used as measurement units for SCADA/EMS-systems. Their integration in the state estimation might reduce the errors but does not result in a dynamic view if they are used together with measurements that are not time-synchronized. In the future the two systems might be combined and future generations of SCADA-systems may offer system protection functionality based on a dynamic system view.

The setup in figure 2 combines and enables two different design principles of wide area protection algorithms. First, all measurement data are communicated to and concentrated in the SPC where algorithms are running to indicate instabilities and to determine and take stabilizing actions. Second, as far as possible, parts of the algorithms or special algorithms are running in a distributed way in the System Protection Terminals. In this case the direct communication between these terminals is used. The question which application needs which part of the setup depends on the kinds of instability to be addressed and on the availability of the communication channels.

B. Applications

The general system setup in Fig. 2 for a wide area protection system allows the implementation of several applications for different kinds of instabilities.

The SPT allows the realization of improved protection applications on PMU basis. A coordination of protection devices can also be realized by the direct communication between the terminals. But an adaptive protection has to be developed most carefully because this basic protection is the last action of defense against disturbances. But for instance a self-diagnosis within a certain terminal may be used as helpful additional input information for neighboring ones. Caused by an out of operation status of a terminal, the neighboring time settings can be adapted to be faster without changing the basic protection strategy.

The small signal angle instability control between different areas can also be realized on this direct base. But if several changing oscillation modes of the power system have to be considered, algorithms in the system protection center takes advantage. A modal estimation is reported for example in [6]. A system wide power system stabilizer is proposed based on wide area phasor measurements [7]. For such an application angle information from different oscillating generators must be transmitted to each of the generators and used as multiple input signals for the PSS.

The applications above can be realized either with a few directly coupled SPTs as well as with a SPC. In contrast, frequency and voltage instability need a system view and can not be realized in a decentralized way. Whereas the frequency itself can be detected for certain areas of a system, the stabilizing actions like load shedding, generation rejection or coordinated islanding need a detailed view for their optimized determination. A coordinated handling of frequency instability needs the information, which power units are operating at which level and what is the actual load pattern and level.

Also, voltage stability is usually a system wide or wide area phenomenon, for which a system model is required to determine stabilizing action in an optimal way. The power margin calculation ([8][9]) as the most useful stability indicator needs a system model. Remedial actions for voltage instabilities can only be optimized if the actual situation of the observed area is known.

The information about a certain area can be determined with a purely PMU-based state estimation [10]. This state estimation uses a linear model and is therefore much simpler and faster than the conventional one. Because a wide area protection system is additional to classical protection and SCADA/EMS systems a certain redundancy of these systems can be assumed. Therefore the redundancy of the PMU-measurements is not critical and can be limited in comparison to the SCADA redundancy. The worst situation would be that the observed area is restricted by PMU failures. The algorithms must know how to operate within such a situation.

For special applications where a system model is not available, e.g. at boundary regions of a power system, alternative local solutions can be realized within one SPT [11] or a few coupled ones [12].

All in all the proposed structure is adaptable to available communication channels and supports state of the art algorithms for wide area protection. In the following the emergency voltage stability control is discussed in detail.

IV. Emergency Voltage Stability Control

A. System Setup

The system setup to address voltage stability control observes a critical area. Observable in this sense means that it is possible to get all information with the desired time synchronisation for both topology detection and state estimation of the observed area. Therefore the PMUs are placed in a way to fulfil both criteria [13]. Fig. 3 shows the system setup for this case. In the SPC the model of the observed area is used for stability assessment and determination of stabilising actions.

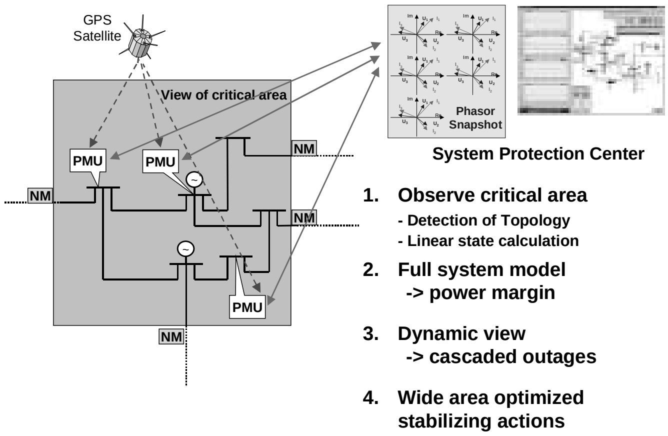

Fig. 3. System setup of wide area protection system for emergency voltage stability control

B. Basic Concept

For the problem of emergency voltage stability control the two phenomena of short and long term voltage instability must be addressed.

If a system is in normal operation, only cascaded or combined outages lead to instability. In most of the practical system collapses long term unfolding instabilities occurred. The reason is that after the initial contingencies the weak situation was not detected well, following events were not foreseen and no appropriate remedial actions are taken. Therefore, either long-term voltage instability or a following event caused by protection mismatch occurred. In both cases the complexity of the problem is beyond that can be foreseen with pre-calculations on N-x base. Therefore any algorithm must be triggered and run after the first events.

After a contingency occurs, the system is in a dynamic phase, which is in the case of long-term voltage instability determined by Under Load Tap Changers (ULTC), overload capacity of generators and load recovery [14][15]. This characteristic leads to a retarded behaviour, which may lead to a collapse. The idea is to predict this collapse directly after an event.

In principle two kinds of predictions are possible. The first way is to start with the steady state situation given by a SCADA-system together with the contingency information e.g. the tripping of a line according to Fig. 4.

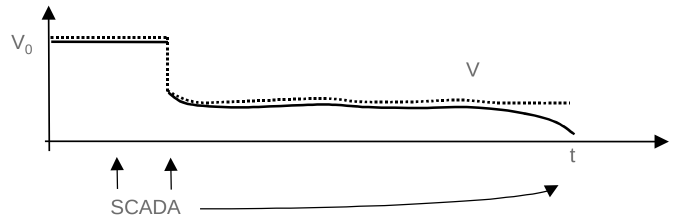

Fig. 4. Long-term voltage instability prediction based on steady-state SCADA-data and contingency trigger

A dynamic model of the power system can be integrated over time to determine if there will be a stable state or a collapse [16]. This approach has the drawback that during the dynamic phase no accurate measurement values are available and therefore the prediction can not be updated with time. Another drawback is that the load dynamics resp. the load recovery characteristic changes during the day and during seasons. This leads to an unforeseeable error.

The here proposed prediction algorithm which is described in detail in [17], uses a wide area measurement system based on PMUs to get a dynamic view of the power system as described above. After a contingency, a sliding data window is used to determine the actual load characteristic. A dynamic model is fed with this information. The equilibrium of this model is determined without a time domain simulation. If there is an equilibrium, the system is predicted to be stable, otherwise the system will collapse. Fig. 5 shows the principle of this approach. The model can also be used for the determination of stabilising actions.

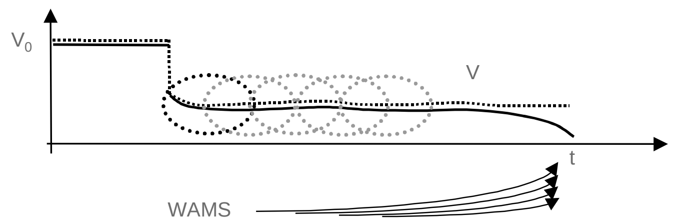

Fig. 5. Long-term voltage instability prediction based on dynamic wide area measurement data

If there is no time to perform the prediction, which means that the system suffers a short-term voltage instability, either predefined actions on a system base or conventional protections like under-voltage protection schemes are acting. The predefined actions have to be determined continuously after a contingency to be prepared for at least the following one, if the time allows. One possible realisation is shown in [18]. In conclusion the protection scheme is as follows:

- Steady state or predicted stable operation: Predefined actions are determined continuously to act after next contingency
- One contingency occurs (long-term voltage instability): If available and necessary, predefined actions are taken. The prediction process is started and stabilising actions are taken or predefined for next contingency.
- Cascaded contingencies occur (long-term voltage instability): The prediction process is started and stabilising actions are taken or predefined for next contingency.
- Short-term voltage instability: Either predefined system wide actions are taken or conventional protection is acting.

C. *Dynamic Voltage Stability Prediction Algorithm*

The proposed prediction algorithm as one of the wide area protection algorithms will be explained in detail in the following. The steady state equilibrium of the full dynamic system model (1) is determined using a model reduction. $\boldsymbol{G}$ are the power flow equations and $\boldsymbol{z}$ the bus voltage magnitudes and angles. $\boldsymbol{F}$ are the remaining equations and $\boldsymbol{x}$ the remaining state variables.

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{F}(\boldsymbol{x}, \boldsymbol{z}) \\ \boldsymbol{0} &= \boldsymbol{G}(\boldsymbol{x}, \boldsymbol{z}) \end{aligned} \tag{1}$$

At first, all short-term transients in the model are neglected. ULTC, voltage controllers, reactive power limiters and load characteristics can be approximated by their steady-state behavior. To find the equilibrium of the remaining equation system (2) a Newton-Raphson algorithm is applied. In (2) $\boldsymbol{F}_s$ are the simplified equations with the reduced state vector $\boldsymbol{x}_s$.

$$\begin{aligned} \boldsymbol{0} &= \boldsymbol{F}_s(\boldsymbol{x}_s, \boldsymbol{z}) \\ \boldsymbol{0} &= \boldsymbol{G}(\boldsymbol{x}_s, \boldsymbol{z}) \end{aligned} \tag{2}$$

With this model simplification the transient characteristics are separated from the interesting steady-state ones.

To set up the full algorithm the following steps has to be performed. While the system is running in a steady-state situation, the steady-state values of bus voltages V_0 and load powers P_0 and Q_0 must be traced and contingencies such as changes in the topology must be detected. After a contingency is detected the parameters of an applied load model, which describes the voltage dependency of the power, must be determined.

A general load model is shown in (3). P_0 and V_0 are the base power and voltage before the contingency and $\dot{P}$ and $\dot{V}$ are the power and voltage gradients at a certain time step *t*. $\boldsymbol{p}$ is a vector containing all unknown load parameters.

$$P(t) = f\left(P_0, V_0, \dot{P}(t), \dot{V}(t), V(t), \boldsymbol{p}\right) \tag{3}$$

An example of a typical load model is the Hill and Karlsson model in (4), which shows the typical load recovery characteristic after voltage steps [19]. But also any other model, like e.g. composite ones, can be used.

$$P = -T_p \dot{P} + P_0 \left(\frac{V}{V_0}\right)^{\alpha_s} + \frac{P_0}{V_0}\dot{V}\ T_p\ \alpha_t \left(\frac{V}{V_0}\right)^{\alpha_t - 1} \tag{4}$$

To determine the load parameters, a sliding window of voltages V at each bus and feeder loads P, Q are collected. $\dot{P}$ and $\dot{V}$ are the mean values of the gradients between two timely neighboring measurement points. A set of load equations (3) for different time steps within this window builds a nonlinear equation system, which has to be solved for the unknown parameters $\boldsymbol{p}$. This equation system can be solved with a non-linear solver algorithm (e.g. Nelder-Mead). When the number of equations is greater than the load parameters the equation system is over-determined, which increases the accuracy and robustness of the results. Alternatively, a simplified linear solving algorithm is proposed in [17].

The algorithm must be calculated for each feeder resp. sum of feeders of a substation to determine the behavior of all loads in the system. If it can be seen that the loads behave similarly in a certain area of the system, the number of calculations can be reduced to single examples for each area.

The determined load parameters are fed into the simplified system model to be solved for the equilibrium as described above. This equilibrium point is the predicted state of the system, which might be tens of seconds in the future. If no equilibrium is found, the transient phase will end in a collapse. In both cases a positive or negative power margin can be determined with a continuation power flow to assess the stability of the system [8][9].

D. Simulation Examples of a Real Power System

The following example of the real power system is based on the network data of a real South American system. This example demonstrates the applicability of the approach to a real system. The system is characterized by a large load area in the center of the system and generation areas about 400 km in the north and south. Fig. 6 shows the load center and the northern part of the investigated power system.

The contingency situation for the simulation is a cascaded outage of two lines between the load center in the middle of the system and the northern generation area at 2s resp. 20s. These contingencies lead to a critical situation close to the stability boundary but not to a collapse.

Fig. 7 shows the power margin PM for the predicted and the non-predicted case. The sensitivity after the first contingency is still low. Therefore the effect of the prediction is also low. The higher accuracy resulting from the prediction is only 1 %. After the second contingency the effect is stronger, because the system is operating in a more sensitive resp. non-linear operational point. From the beginning of the prediction after the second contingency it needs about 50 s until the non-predicted power margin PM is the same as the predicted one. Therefore the forecast of the proposed algorithm is about 50 s in this example. Therefore the scope for stabilizing actions is extended by this time interval.

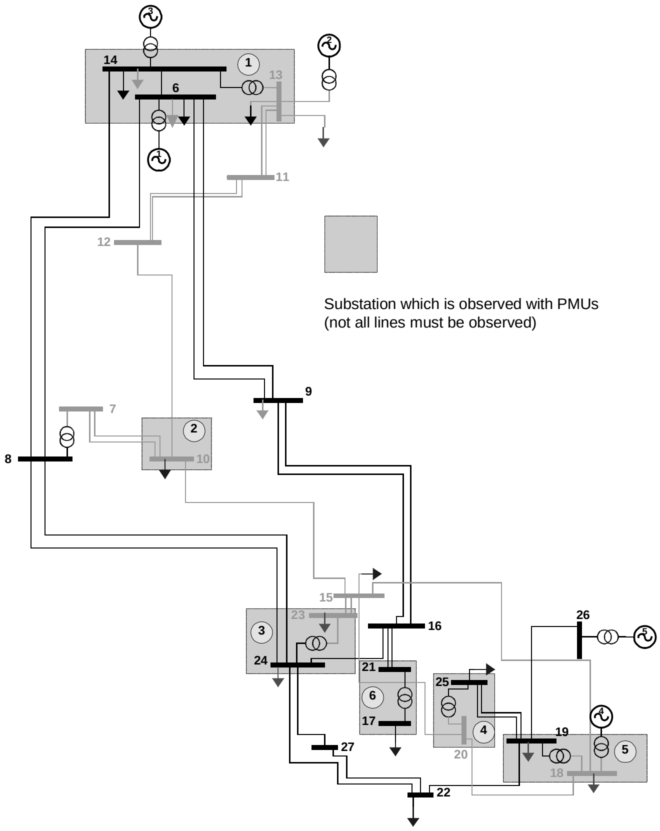

Fig. 6. Observed area of investigated power system

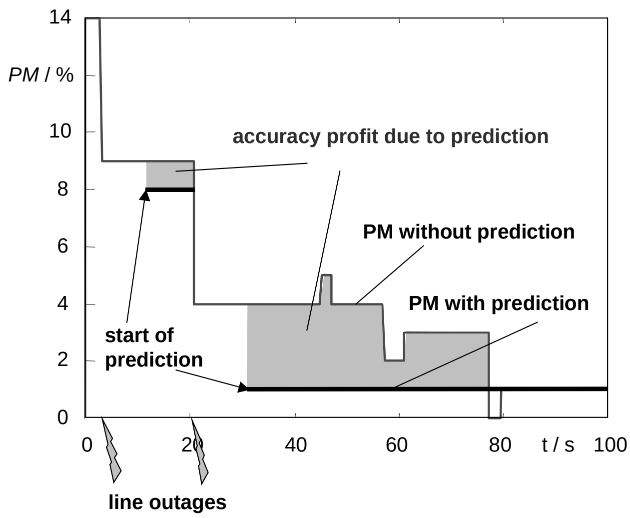

Fig. 7. Power margin PM as percentage of the base load P_0

As a result, the criticality of the system will be predicted earlier and also remedial actions can be taken without delay.

Up to this point only line trippings are considered as contingencies. The described algorithm covers all kinds of contingencies without any changes. The contingencies in this case are topology changes as line or transformer outages resp. generation outages. Load increase can be assumed as steady state covered by the conventional approach and load tripping stabilizes the system, which is uncritical for the stability. The algorithm to determine the kind of contingency and triggering the transient voltage stability prediction and the following continuation power flow has to consider all these cases.

V. Conclusions

The paper proposes a wide area protection system applicable against different kinds of instabilities. The requirements for the wide area protection system are a dynamic wide area view of a critical area as base for stability assessment and determination of remedial actions. The proposed approach bases only on time synchronized Phasor Measurement Units, which allow a dynamic view of the system. The general setup of the proposed system allows implementing applications in both a distributed local or a centralized way dependent on the availability of communication channels and special needs of the application.

The main focus of the paper lies on the application for emergency voltage stability control. The use of the system setup for this application is defined in detail. A system view based on linear state estimation for a certain critical area of a power system builds the base for the stability assessment and determination of remedial actions. A special algorithm is introduced using the dynamic view for cascaded outages together with long-term voltage instability. Considering the long-term system dynamics a more precise and early detection of instabilities is possible. Therefore remedial actions can be taken earlier and more optimized than in conventional systems.

The next steps of research will apply the proposed system for more kinds of instabilities to get a common solution, which also reacts on combinations of instabilities.

VI. Acknowledgment

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VIII. Biographies

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